An Investigation and Analysis of the Vestibulo-Ocular Reflex in a Vibration Environment

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Helmet Mounted Displays (HMDs) and their integration into military systems have greatly improved. However, previous research has demonstrated degraded visual performance when an HMD user is subject to whole-body, low-frequency vibration. This effect has been attributed to the effect of the Vesitbular-Ocular Reflex as it stabilizes the eye with respect to the external environment, causing eye movement with respect to the HMD. This research sought to understand the VOR as a function of whole-body, low-frequency, z-axis vibration. A human subject experiment was executed to measure the effect of whole-body, low-frequency vibration on eye movements recorded with Electro-oculagraphy (EOG) while performing visual fixation tasks on an HMD. The results indicate that during fixation on a stationary target, the magnitude of VOR-driven eye movement was greatest for a vibration frequency range of 4-6 Hz. The findings are consistent with previous research in visual performance.

The Head- or Helmet-Mounted Display (HMD) continues to advance technologically, but also in its applications. For example, F-35 pilots are highly dependent on their HMD as it has replaced the heads-up and panel displays employed in previous military aircraft. By eliminating practically all other in-aircraft displays, the HMD reduces aircraft weight and power, while providing novel capabilities, such as the ability to "look through" the hull of the aircraft below the canopy. HMDs have also become a necessary component of the human interface within many rotor-wing platforms and are being used by dismounted personnel and personnel driving land based vehicles. HMDs are popular in these applications as they provide critical information with increased mobility (Geiselman and Havig, 2010). The fact that HMD permits the designer to display information within the user's visual field, regardless of head location, improves performance by enhancing situational awareness (Velger, 1998).

While HMDs have provided positive improvements in aircrew and battlefield performance (Daetz, 2000), many significant issues remain with this technology, such as visual clutter, attentional capture, and inattention blindness that can occur from using bright, collimated displays, such as HMDs (Gibb et al., 2010). Another significant problem occurs when these displays are viewed by an operator in an environment that is undergoing low-frequency vibration. Under these conditions the effectiveness of the HMD decreases sharply due to a loss in perceived resolution that is thought to occur as a result of the human Vestibular Ocular Reflex (VOR) (Rash, et al, 2009). While most fixed-wing, jet-propelled aircraft are not subject to these low-frequency vibration regimes for significant lengths of time, propeller driven aircraft occupants, helicopter operators, and land vehicle drivers can routinely experience these vibration ranges throughout a mission. Further, certain fixed-wing jet aircraft are subject to buffeting which exposes the pilot to similar vibration, although for relatively short intervals of time (Daetz, 2000).

While previous research has demonstrated reduction in human visual performance when using HMDs in environments undergoing vibration, these studies have generally not sought to understand the relationship between eye and head movement within these environments. Therefore, the focus of this research was to understand the motion of the eye and head as the user performs simple visual tasks. It is hoped that this information can aid the design of future vibration compensation systems.

Background

Vibration occurs in six-degrees of freedom, e.g., x, y and z dimensions, as well as roll, pitch and yaw. Vibration is highly dependent on many different variables, including aircraft type, seat type, body size, muscle tone, posture and helmet weight (Daetz, 2000). The human body is physically sensitive to vibration. Numerous studies have established that whole-body resonance occurs within the frequency range between 4 and 8 Hz during exposure to vertical vibration. Head pitch magnitude occurs most severely between 4 and 8 Hz as a result of the forces that occur during resonance (Smith, et al, 2007). Head translational and rotational transmission is generally greatest between 0 and 10 Hz, while most vibration occurring at frequencies greater than whole-body resonance, e.g., greater than 10 Hz, is typically dampened before reaching the head (Paddan and Griffin, 1988).

Vibration has been shown to degrade human visual performance within a number of studies. Lewis and Griffin demonstrated that reading performance was degraded most severely for frequencies between 5 and 11 Hz, resulting in reading error rates up to 20% for subjects seated in a vibrating helicopter seat (Lewis & Griffin, 1980). A separate study, in which participants were subject to display-only, participant-only, and both display-participant vibration, found that the reading performance of the display-only vibration test rated significantly worse than the other two (Moseley and Griffin, 1987). These vibration effects also extended to more complex tasks associated with military operations. In general, the highest or most severe visual performance degradation occurs at frequencies in which vibration is transmitted to the head. While various research studies have demonstrated that the frequency range of the most severe visual performance degradation is between 4 and 6 Hz, at a magnitude of 1 m/s^2 or .1 g, this research has also shown that visual performance can be adversely impacted at higher frequencies up to 20 Hz (Rash, 2009; Velger, 1998; Griffin, 1990). In addition, high intensity vibration beyond 20 Hz that does reach the head can cause visual blurring due to resonance behavior in the eye or associated structures (Griffin, 1990).

The human eye generally moves in fast saccadic movements between relatively stable fixation points. Once fixated on a point, the human eye then integrates information from the scene. An alternate eye movement behavior occurs when a user is tracking a moving object. During these events, the eye moves in smooth pursuit, often referred to as fixation reflex during which the eye is fixated on an object of interest and follows this object in space, typically without the need for head movement. However, for fast moving objects, smooth pursuit eye movements can be coordinated with slow head movements to permit the object to be tracked over large distances. Importantly for either type of eye movement, the eye time-integrates the information from the scene, permitting the object of interest to be imaged onto the retina and captured at a high signal to noise ratio.

The degradation of visual acuity and thus task performance due to vibration when using an HMD has been attributed to the eye and the associated motions induced by the VOR within vibratory environments. When rotational (roll, pitch and yaw) head movements, such as those caused by vibration, are introduced to the head, the eye responds with a reaction known as VOR. The VOR occurs when the semicircular canals in the ear detect head motion, sending a signal to the eye muscle, which induces the eye to involuntarily move in the direction opposite to and near the same magnitude as the movement of the head (Tabak, et al, 1997). Some studies have found the VOR to be effective only at frequencies up to 10 Hz, though other research suggests that the VOR is operative in frequency regimes of 20 Hz and higher (Griffin, 1990). For example one study found that the errors associated with the tracking of a target with both the eyes and the head increased nearly linearly with increased vibration amplitude for frequencies between 2 and 20 Hz (Shoenberger, 1972)**.**

The VOR allows whatever image is being focused on, to remain in the center of the retina while the head undergoes motion, facilitating the integration of information from the image. This reflex is most noticeable when doing high-impact activities such as running or jumping. During these activities, the VOR allows the world around us to be stabilized in space by moving our eyes to adjust for head motion and allowing us to fixate on objects within our environment. However, the VOR is not effective in the presence of translational head motion, because this head motion causes an angular displacement of the image, which is dependent upon the distance of the object from the eye, which the VOR cannot correct (Griffin, 1990). The VOR assumes that our natural world is stationary and we move within the world reference frame. Therefore, when visual information is provided on an HMD which moves with the head, this VOR response becomes inappropriate as the image provided by the HMD is stabilized with respect to the head. Since the VOR causes the eye to move to compensate for head movement, this compensatory eye movement results in relative motion of the display with respect to the eye.

Another complicating factor is that it cannot be assumed that the VOR correctly compensates for head motion under all circumstances. The pursuit, or fixation reflex, allows the eye to follow the data or text at vibrations at around 1 Hz, but at frequencies higher than 3 Hz, reading the vibrating display isn't only difficult, it becomes nearly impossible as the fixation reflex can no longer keep up with the movement caused by vibration. (Griffin, 1990) Therefore, it is believed that the VOR induces relative motion between the HMD and the human retina that is not predictable. Unfortunately, while the VOR is an essential part of our human composition, when viewing HMD's while seated in environments undergoing low frequency vibration, e.g., less than 10 Hz, the VOR can cause significant degradation in performance and this degradation may not be predicted by measuring the motion of the user's head alone. Further, the head is not likely to vibrate synchronously with the environment as the human skeleton and tissue is likely to affect the transmission of vibration from an environment to the user's head.

While vibration and the associated VOR effect are well documented, little has been done in the past 40 years to compensate for this effect. The rudimentary solution has been to simply increase the size of the text or graphics (Griffin & Lewis, 1978), space out the text (Griffin, et al., 1986) or change contrast levels (Moseley &

Griffin, 1987) on the display. These adjustments result in improved reading performance under vibration conditions. Unfortunately, these recommendations run counter to HMD technology investment to further the resolution of HMDs in an effort to increase the rate of information transfer between the system and the human operator.

Another form of compensation involves image stabilization, by attempting to move the displayed information synchronously with the motion of the head to compensate for the VOR. Many compensation methods have been attempted, including measuring acceleration signals from the helmet and applying a double-integration filter to displacement and amplifying this signal to the HMD electronics to adjust the image accordingly (Wells and Griffin, 1984). Another compensation method applies adaptive noise cancellation to create a compensation input for an HMD. This type of compensation takes into account the reference of a primary signal, often from an aircraft mounted accelerometer which measures vibration levels, and then filters it through a biodynamic transfer function, which estimates the seat to head vibration transmission based on the aircraft type and flight regime. This filtered signal then moves information on the HMD synchronously with the sensed aircraft vibration to provide image stabilization for viewing tasks (Lifshitz and Merhav, 1991; Velger, 1998). A third method involves applying a conventional notch/lag filter to remove the effect of head rotation (Daetz, 2000). While each of these methods found varying degrees of success, the resulting algorithms suffered from inaccuracy and latency issues. Because VOR-induced eye movement was not understood, it is unclear whether the error is due primarily to latency or whether our lack of understanding of the VOR when viewing an HMD produced unexpected errors.

Improving the accuracy of compensation algorithms requires a more in-depth understanding of the VOR. VOR research has been conducted in the medical field with a focus on determining patient vestibular deficiencies. Two such studies were conducted by applying a helmet apparatus to perturb the subject's head in the low-frequency domain. One study analyzed the VOR effect based on fixation of a stationary target, while later research incorporated head-free tracking of a moving visual target. Both studies found that the VOR was predictable and acted linearly up to approximately 4 Hz. However, they found that the dynamics of the VOR began to vary at greater than 4 Hz (Tabak, et al., 1997; Tangorra, et al., 2004). The Tabak study, which involved fixation on a target, found that VOR gain *decreased* up to 8 Hz, and then increased. The Tangorra study, which involved tracking a moving target, found the VOR gain *increased* at frequencies greater than 4 Hz. Both studies concluded that the VOR has non-linear dynamics at higher frequencies and suggested the need for further evaluation. These studies did attempt to control the vibration of the head by using a head perturbation system and did not induce whole-body vibration.

The present study, conducted at vibration frequencies encountered by rotorcraft and during buffeting, sought to validate these findings and provide a foundation to further research on compensation algorithms.

Methods

Participants

Six volunteers between the ages of 20 and 26 years with a mean of 23 years participated in the study. Participants had not experienced any vestibular anomalies, including inner ear infections, within the month preceding the investigation or reported any discomfort or pain symptoms associated with the musculoskeletal system. Additionally, female participants were not pregnant and did not have breast implants. Individuals requiring glasses or hard contacts were precluded from participating in the experiment.

Apparatus

During the experiment, participants wore an HMD system, which supported visual tasks. A custom HMD was designed and built to accomplish this goal. This system included a typical Air Force Flight Helmet, equipped with a visor. A binocular display was mounted on the visor, which permitted a VGA image to be provided to each eye with a field of view of 30 degrees. This helmet supported the six electrodes, attached to the user's face, used to measure the movement of the eyes with respect to the head via EOG. EOG measurements were facilitated using a BioPac MP150 which permitted EOG signals to be obtained at a sample rate of 1000 Hz. This procedure recorded the potential difference between the electrodes as the eye moved from the center, neutral position towards the electrodes. Additionally, the BioPac system was equipped with a 3 DOF accelerometer, which was attached to a custom fit mouth guard for each participant to permit head acceleration to be measured.

This study was conducted in the Single-Axis Servo-hydraulic Vibration Facility supported by the Air Force Research Laboratory's 711th Human Performance Wing. The human-rated single-axis vibration table is capable of generating various vibration signals in the vertical or Z direction. A rigid seat with seat pan and seat back cushions was mounted on top of the platform. For this study, single sinusoidal frequencies were generated between 0 and 10 Hz in 2 Hz increments with an amplitude of 0.1 g Peak.

Experimental Procedure

During the experiment, participants completed two tasks. Task A required the participant to fixate on a centered, stationary target, while Task B required the participant to fixate on a moving target which moved around the display in a rectilinear pattern. This target increased in velocity from each apex in the pattern, reaching a rate of 190 pixels per second and maintaining this rate before decelerating as it approached the next apex. Participants completed two trials, performing each task at each vibration frequency on two separate days.

The participants were exposed to a vibration condition for 20 seconds and then performed the task for 15 seconds. Once completed, the frequency of vibration was changed and the task repeated for the subsequent vibration condition. The task order, as well as frequency exposure order, was varied over the two trials.

Data Analysis

The resultant EOG recording data were processed and analyzed using code developed in MATLAB. Independent variables for this research included the vibration frequency and trial. The primary dependent variable of interest was the magnitude of vertical eye movement, indicated by a change in the EOG signal measured in mV.

The vertical component of the EOG data was processed using the following steps. First, the signal collected during the fixation in the first task or horizontal target tracking in the second task was segmented from the data for further analysis. The segmented data was first filtered to eliminate low-frequency drift in the EOG signal by applying a low-pass filter. A second filter was applied to determine high amplitude values caused by blinks or other erroneous eye movements and this data was segmented out of the data stream. Finally, the remaining data were analyzed to determine the Root Mean Square (RMS) value in mV for each participant at each frequency condition during each trial. The RMS was calculated using Welch's method (Diez, 2008), which estimates the power spectral density estimate (PSD) at different frequencies using an overlapping window principle and computing the discrete Fourier Transform. The resulting array was the RMS value as a function of frequency for each of the two tasks. The peak frequency was then selected and was found to consistently correspond to the frequency of the input signal for all frequencies between 2 and 10 Hz.

Results and Discussion

An analysis of variance (ANOVA) was applied to both of the individual tasks to understand whether there was a statistical effect of Frequency or Trial on the RMS of the EOG signal. Participants were treated as a random effect within this model. The ANOVA for the stationary fixation found that Frequency had a significant effect on the eye magnitude value ($F(4, 20.76) = 23.29$, $p<0.0001$). To further understand this interaction, a post hoc Tukey test was conducted on the 5 vibration frequency conditions to determine statistically significant differences between the levels. The Tukey test used applied a 95% confidence interval ($\alpha = .05$) and calculated the Least Square Values (LSM) of the data at each frequency. The mean RMS value at 4 Hz was significantly higher than the mean RMS values for the remaining frequencies, while the mean RMS value for the 6 Hz frequency condition was significantly higher than the mean RMS value for the 8 and 10 Hz conditions. Figure 1 shows that the mean RMS values increase dramatically as the frequency is increased from 2 to 4 Hz and then decreases with further increases in frequency.

The same ANOVA model was applied to Task B, the moving fixation task. This analysis found that, as expected, Frequency had a significant effect on the eye magnitude value ($F(4, 20.93) = 22.57$, $p<0.0001$). A post hoc Tukey test was again conducted to determine statistically significant differences between the vibration conditions. As in Task A, the results for Task B found that the mean RMS value for the 4 Hz condition was significantly higher than all other conditions, while the mean RMS value for the 6 Hz condition was significantly higher than the mean RMS values for the 4 and 10 Hz conditions. Figure 2 shows that, as in the single point fixation task, the magnitude of the mean RMS value increases to a peak at 4 Hz and declines for higher frequencies.

Previous research regarding the impact of the VOR on visual performance in vibration conditions had relied only on performance measurements, such as reading or aiming errors. This research had indicated an increase in aiming error and acuity decrements (Velger, 1998), as well as a rise in reading errors (Wells and Griffin, 1990) within the 4 to 6 Hz range. Additionally, the literature suggested that as the vibration frequency increased beyond 6 Hz, the body would dampen the vibration and decrease the transfer of vibration to the head (Rash, 2009). The results of the present study confirmed that the highest VOR-induced eye movements did in fact occur at this 4-6 Hz range, while steadily decreasing with increasing frequency. Overall, the findings for analysis performed on each task found that the RMS amplitude of the vertical eye movements as a function of frequency followed the same general pattern

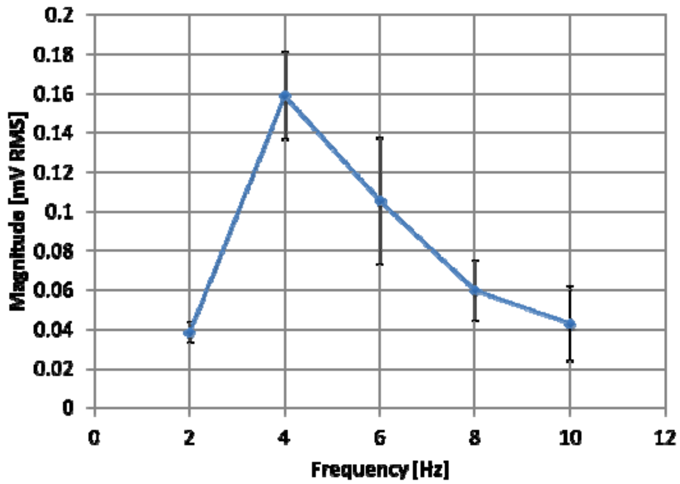

Figure 1. Mean RMS value (in mV) as a function of vibration frequency, with one standard error for Task A

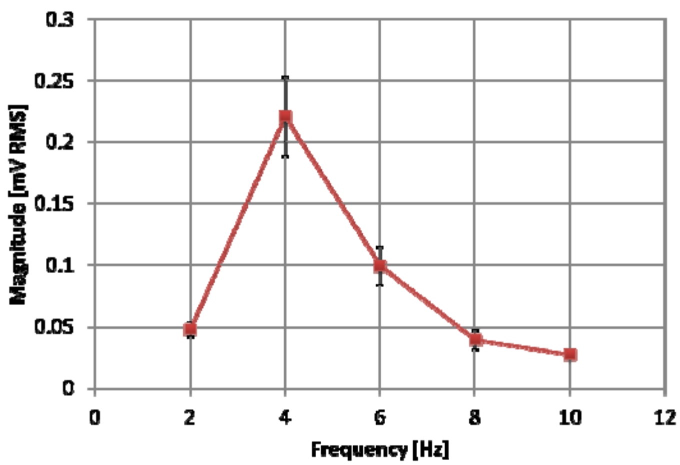

Figure 2. Mean RMS value (in mV) as a function of frequency, with one standard error for Task B

Conclusions

This investigation delved into a research area that until now has been largely overlooked, namely investigation of the compensatory eye movement of the VOR for an individual undergoing whole-body vibration while wearing an HMD. This research allowed a participant to perform visual tasks on an HMD, while also capturing the participant's eye movement via EOG. The results from fixation and tracking tasks corroborated with decades of visual performance research, finding that the VOR-induced eye movement as a function of vibration frequency has a maximum magnitude in the 4-6 Hz range. This study gathered data over only a small sample of participants and does not lend itself to understanding individual differences in eye movements as a function of frequency. However, this investigative effort was able to show that eye movement data can be collected in a vibratory environment and that it provides information that is consistent with past performance research. Further analysis of this data should focus on a comparison of the tasks to determine an effect, if any, of adding motion to a task. Additionally, the data measuring head acceleration needs to be examined in an attempt to better understand the relationship between head and eye movement in an HMD application.

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